NUCLEAR BIMODAL NEW VISION SOLAR SYSTEM MISSIONS

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Abstract

This paper presents an analysis of the potential mission capability using space reactor bimodal systems for planetary missions. Missions of interest include the Main belt asteroids, Jupiter, Saturn, Neptune, and Pluto. The space reactor bimodal system, defined by an Air Force study for Earth orbital missions, provides 10 kWe power, 1000 N thrust, 850 s Isp, with a 1500 kg system mass. Trajectories to the planetary destinations were examined and optimal direct and gravity assisted trajectories were selected. A conceptual design for a spacecraft using the space reactor bimodal system for propulsion and power, that is capable of performing the missions of interest, is defined. End-to-end mission conceptual designs for bimodal orbiter missions to Jupiter and Saturn are described. All missions considered use the Delta 3 class or Atlas 2AS launch vehicles. The space reactor bimodal power and propulsion system offers both; new vision "constellation" type missions in which the space reactor bimodal spacecraft acts as a carrier and communication spacecraft for a fleet of microspacecraft deployed at different scientific targets and; conventional missions with only a space reactor bimodal spacecraft and its science payload.

## INTRODUCTION

In past studies (Yen 1993) the value of nuclear electric propulsion (NEP) for delivering large payloads to the outer planets with 6 to 8 year burn times has been shown. An alternative approach is to use chemical propulsion, low mass payloads, and gravity assists to minimize the use of NEP and focus on the benefits of high power to increase data transmission rates and therefore mission science return. Chemical propulsion, low mass payloads and gravity assist trajectory make outer planet orbiter missions possible with NEP bum times of only 2 to 4 years (Zubrin 1994). However to accomplish such missions Titan class launch vehicles are required. In analyzing inner solar system missions it was found (Zubrin, et al 1992) that if a space reactor can generate electric power and also heat hydrogen or ammonia to generate moderate thrust (1 OOON) it offers strong mission benefits over NEP. A Space Reactor Bimodal (SRB) power and propulsion system can generate thrust with specific impulses over 800 s. The SRB system with the gravity -assisted trajectories enable outer planetary missions, which feature several microspacecraft at one planet, substantial scientific data, and moderate cost launch vehicles.

There currently is a NASA led effort underway to develop planetary autonomous 10 kg microspacecraft (Collins, et al 1995). Several of these microspacecraft could be carried to scientific target by the SRB spacecraft to create networks of orbiters and landers for exploring an outer planet and its moons. The scientific data from each of the microspacecraft could be relayed to Earth by the high-powered bimodal spacecraft. For these reasons the SRB system, either by itself or in combination with the coming generation of planetary microspacecraft might provide for future "virtual reality" scientific exploration of the outer planets. The technology baseline chosen is the bimodal reactor system defined in recent studies (Weitzberg, et al 1995) for the US Air Force Phillips Laboratory. This bimodal reactor system produces 10 kWe of power, 1000 N of thrust at an Isp of 850 s using hydrogen propellant, 1880 N of thrust at an Isp of 450 s using $NH_3$ propellant and has an estimated mass of 1500 kg. The electric propulsion subsystem consists of ion engines using Xenon propellant with a specific. impulse of 5000 s and a specific mass of 18 kg/kWe. Hydrogen tanks are assumed to have a dry mass equal to 15 % of the propellant they contain. It is assumed that microspacecraft are available with dry masses of 10 kg capable of carrying miniaturized instruments and performing all necessary spacecraft functions except interplanetary communication.

## SPACE REACTOR BIMODAL SPACECRAFT (SRB)

A 10 kWe SRB flight spacecraft was defined and is shown in Figure 1. A mass estimate for the SRB spacecraft configured for a Jupiter or Saturn orbiter mission using a 2-year Earth gravity assist (EGA) is given in Table 1.

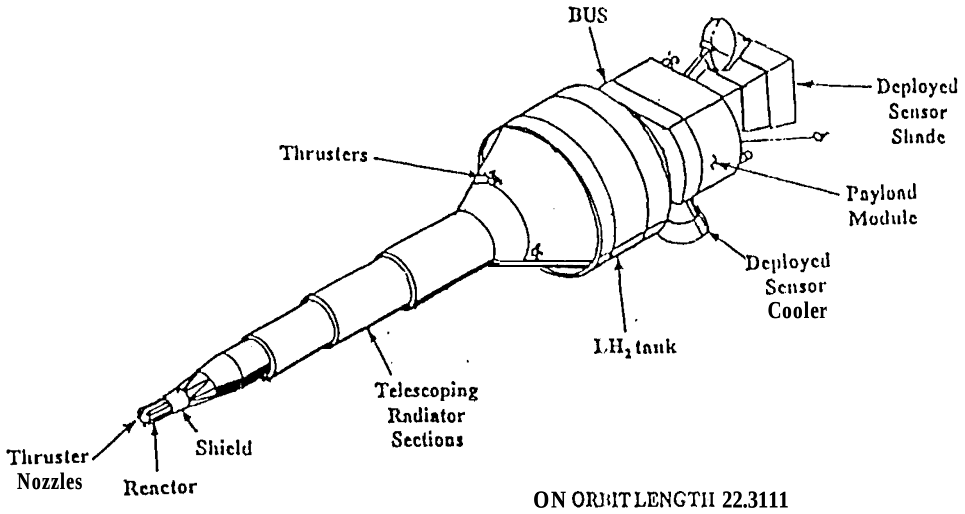


FIGURE 1. 10 kWe SRB Spacecraft.

**TABLE** 1. Mass of 10 kWe SRB Spacecraft

| | |
|---|---|
| Science Instruments | 100 kg |
| Spacecraft Total | 425 kg |
| Space Reactor Bimodal Subsystem | 1460 kg |
| Electric Propulsion Subsystem (Xe-ion 18 kg/kW) | 180 kg |
| NH3 Propellant & Tanks | 370 kg |
| Xenon Propellant & Tanks | 490 kg |
| Hydrogen Propellant & Tanks | 3325 kg |
| Total Mass in Low Earth Orbit | 6350 kg |

An Atlas 2AS has a LEO launch capability of about 8000 kg. Therefore, the above spacecraft would have a launch margin of about 26 % (Zubrin and Mondt 1995).

## JUPITER MISSIONS

For our SRB mission to Jupiter we consider two options. The first of these is a mission in which the spacecraft carries 20 kg of instruments (a multi-spectral camera plus some plasma science receivers and the dual purpose communication and radar dishes) and a set of microspacecraft for delivery to various destinations in the Jupiter system. Each microspacecraft is assumed to have a mass of 10 kg and to be sufficiently radiation hardened to perform at its appointed station in the Jovian system. Four of the microspacecraft are orbiters, to be delivered into elliptical orbit around each of Jupiter's four Galilean satellites. Two of the microspacecraft are lander/rovers, to be delivered to the surface of Ganymede and Callisto, Jupiter's largest satellites. In addition there are two aeronomy orbiters to be delivered into low orbit about Jupiter, and two atmospheric probes to be delivered into Jupiter's atmosphere. The mass including propellant of the microspacecraft are shown in Table 2.

Table 2. Mass of Microspacecraft for Jupiter

| | Jupiter | Io | Europa | Ganymede | Callisto |
|---|---|---|---|---|---|
| Orbiter | 13 kg | 60 kg | 37 kg | 22 kg | 15 kg |
| Lander | 20 kg | 156 kg | 83 kg | 61 kg | 39 kg |

The SRB spacecraft initiates the Jupiter exploration phase of its mission by means of a 0.5 km/s high-thrust bum using bimodal direct thrust with NH3 propellant (450s Isp) which captures the spacecraft into an elliptical Jupiter orbit with a periapsis of 5 RJ and an apoapsis of 158 RJ. This orbit has a period of about 100 days. The low orbital aeronomy and the atmospheric probes are then released at apoapsis and perform small bums which lower their periapsis to the right altitude for their missions. The SRB spacecraft uses electrical propulsion to make its orbit equatorial, and then successively raise its periapsis from 5 RJ, to 5.9 RJ, to 9.4 RJ, and to 15.0 RJ, which are the required periapsis where the microspacecraft to Io, Europa, and Ganymede are released.

With its periapsis set at Ganymede, the SRB spacecraft uses 7 Ganymede gravity assists, which in about 290 days lowers its apoapsis to 26.3 RJ, the orbital distance of Callisto. NEP is used at the apoapsis of each of these orbits to ensure that Ganymede is actually encounter on each pass. After this set of maneuvers has been completed, the spacecraft is now in a 15 RJ X 26 RJ 13 day equatorial orbit and the Callisto payloads are released. Either a series of Callisto gravity assists or a 2.2 km/s AV with NEP apoapsis thrust arcs can be used to reduce the periapsis of the orbit back to 5 RJ, allowing the spacecraft to repeatedly visit Io, Europa, Ganymede, and Callisto on a 9 day orbital cycle. The total science payload mass for Jupiter is 320 kg as shown in Table 3. Referring to (Zubrin and Mondt 1995) there is ample margin for delivery of a 320 kg science payload with an Atlas 2AS launch vehicle.

Table 3. Science Payload of SRB Spacecraft for Jupiter Exploration Mission

| | |
|---|---|
| SRB S/C Instruments | 20 kg |
| (2) Jupiter Atmospheric Gliders | 40 |
| (2) Low Jupiter Orbiters | 26 |
| Io Orbiter | 60 |
| Europa Orbiter | 37 |
| Ganyrnede Orbiter | 22 |
| Ganymede Lander | 61 |
| Callisto Orbiter | 15 |
| Callisto Lander | 39 |
| Total Science Payload | 320 kg |

This mission is extremely exciting scientifically, but is it affordable, given the large number of spacecraft involved? The mission could be an international collaborative project, with the US providing the SRB spacecraft and other nations providing the micro landers, orbiters, gliders, etc. The cost to the US would be about the same as a single SRB spacecraft mission. The countries would only have to pay for their own microspacecraft. Such an international arrangement, would allow this ambitious and excit i ng scientific mission to be undertaken.

As an alternative mission, the SRB spacecraft would carry only its 100 kg science instruments (no microspacecraft) to investigate the Jovian system. The instruments are primarily a set of multi-spectral imaging cameras. When coupled with the spacecraft's high data rate, these would allow both Jupiter and its satellites to be imaged in high resolution, spatially, spectrally, and in time. Such a mission would allow scientists to view actual high resolution multi-spectral movies revealing the changing chemistry of Jupiter's atmosphere in dynamic motion. Of course to accomplish this, a large source of electrical power is necessary. The SRB spacecraft provides this power.

This high powered SRB spacecraft allows each of the Galilean satellites to be imaged at 1 meter resolution in the course of a year. In addition, the high powered X-band dishes on the spacecraft could be used to perform both bistatic and monostatic radar investigations of Jupiter and its Moons, as well as radio science investigations of Jupiter's atmosphere and ring system (Harris 1995). These radar and radio science soundings would be done with about two orders of magnitude better resolution than would be possible with Galileo class spacecraft. Finally, the spacecraft would be able to conduct plasma science investigations, listening for various types of radio noise emitted from Jupiter's atmosphere, ionosphere, and extended radiation belts. This type of science is data intensive, so by exploiting its high communication data rate, the SRB spacecraft mission could exceed the performance of a Galileo class spacecraft in plasma science investigate ions by two orders of magnitude. This mission can be accomplished with a 4.7 year flight time to Jupiter using an Atlas 2AS, a 2EGA trajectory and a 1.3 year NEP bum time.

## MISSION OPERATIONS

Mission operations for the microspacecraft fleet mission could be conducted as follows: The microspacecraft would carry a power source consisting of 20 Wt of RHU thermal power, which could be converted with thermoelectics to 1 We. This would be used to trickle charge an onboard Li-ion battery capable of storing up to 120 W-hrs of electricity. The 20 Wt RHU unit would provide enough heat to support thermal control of the microspacecraft, maintaining key electronic components above -20 C. The microspacecraft would remain dormant until its battery had built up a full charge, then it would wakeup and operate its camera or other instruments until the battery charge dropped to 50 %, after which the microspacecraft would go dormant again. During the time of instrument operation all data acquired would be compressed at about 10:1 and then stored in the microspacecraft's 1 ***Gbit memory.*** Assuming pictures composedof512 X 512 pixels, with 8 bits per pixel, each picture taken by the microspacecraft would require 2 Mb, which after data compression would be 0.2 Mb. With 1 Gb of memory, the microspacecraft would thus be able to store up to 5000 pictures (or comparable non-photographic data) at a time.

The microspacecraft has insufficient power to transmit this data to Earth. However the SRB spacecraft is orbiting through the Jupiter system and occasionally makes a close approach to each of the microspacecraft. The SRB spacecraft would carry a beacon, which would constantly be emitting a signal to anyone listening in the area saying "here I am, here I am. " The microspacecraft would carry receivers tuned to the beacon's signal that would cycle on for 0.1 seconds once every 500 seconds. If the receiver picked up the beacon with a volume above a certain threshold indicating proximity, it would send a signal that would activate the microspacecraft. Upon awakening the microspacecraft would emit a signal that would be picked up by the SRB spacecraft, allowing the two to perform a computer "handshake" in preparation for the dumping of stored data from the microspacecraft to the SRB spacecraft at the time of the SRB'S closest approach. The SRB spacecraft then trains one of its 3 meter dishes upon the microspacecraft. Assuming a characteristic velocity for the SRB spacecraft relative to the microspacecraft of 18 km/s and a characteristic distance of 72,000 km (1RJ), this would imply roughly 4000 s available for transmission. A data transmission rate of about 250 kb/s would thus be required to dump all of the microspacecraft's memory during the SRB'S fly by. Assuming that the microspacecraft carries a 0.1 m X-band dish, transmission at this rate over 72,000 km would require about 6 W of electric power. The total energy required for the data dump would only be about 7 W-hrs, or 5 % of the total microspacecraft battery capacity.

The most unique Jupiter system microspacecraft are the atmospheric gliding probes. The purpose of these probes is to assess chemical composition deep within Jupiter's atmosphere. 'A glider, operating between the 5 bar (-O C) and 100 bar (-250 C) levels of Jupiter's atmosphere, will obtain a depth distance on the order of 100 km. At the 5 bar level the density of the atmosphere is about 0.45 kg/rn3, assuming an airspeed of 100 m/s, a lift coefficient of 0.5, and taking into account Jupiter's gravity of 2.53 times Earth, the required wing area for a 10 kg glider to remain aloft is 0.22 $m^2$. Sail planes are built with lift to drag L/D ratios greater than 20, so using an L/D of 20 the total horizontal glide path of the aircraft during a 100 km descent is about 2000 km and a flight time of 5.6 hours. Within 2000 km of horizontal travel the odds are very high that both updrafts and downdrafts will be encountered. Since the speed of updrafts is much greater than the glider's 5 m/s descent speed a glider which finds such an updraft will be able to ascend by circling in it much as seagulls do on Earth. Using this technique the glider will be able to ascend and descend in a controlled 'manner, repeatedl y sampling the chemistry and other environmental parameters of Jupiter's deep atmosphere. Assuming 1000 km of horizontal travel per descent, about 113 dives would be needed for a given glider to navigate. through 90 degrees of latitude.

Like the other spacecraft, the glider would also be power limited. Therefore it would adopt a strategy of cycling it's instruments on for 0.1 seconds once every 100 seconds, taking a chemistry, pressure, temperature, E and B field and acceleration readings. Such a data set would be about 1000 bits (8 bits each for P,T, E, B, acceleration, and each of 120 chemical substances). If such a data set is taken every 100 seconds, the aircraft will be able to store 10 million such sets in its 1 Gb memory. This is much longer time, 32 years, than the probable time for an encounter between the glider and the SRB spacecraft. This would allow the gliders to transmit all their data to an orbiter relay without the use of a directional antenna. The ability to get frequent reports from the gliders could be enhanced further by using the low Jupiter microspacecraft orbiters as intermediate relay stations for glider data.

## SATURN MISSIONS

Similar missions to the above can be envisioned for Saturn and the other major planets. However each planet has its own particular targets of interest. For example at Saturn, the cloud covered moon Titan is almost of as much interest as Saturn. This suggests the following missions for Saturn. The SRB microspacecraft augmented mission to Saturn begins with the bimodal spacecraft launched by an Atlas 2AS to LEO. The bimodal spacecraft then ejects itself from LEO onto a 2EGA trajectory which returns it to Earth with a C3 of about 80 km2/s2. This is not quite enough to reach Saturn, so after the Earth encounter about 1 km/s of AV (2 km/s with gravity losses included) is generated by electric propulsion to accelerate the spacecraft to a C3 of about 100 $km^2/s^2$, which allows it to reach Saturn in 3.9 years (5.9 year total flight time).

If the mission is launched in a year for which a Jupiter **gravity assist is available** (3 years in a row out of every 12), the 2EGA trajectory becomes sufficient to reach Saturn via Jupiter without NEP acceleration. In this case Jupiter is encountered about 4.5 years **into the mission, at which time if a SRB spacecraft** is operating in orbit around Jupiter a few microspacecraft can be released to reinforce the investigations there, after which the main spacecraft flies on to encounter Saturn about 7 years after launch. In either case., electric propulsion is used to reduce the hyperbolic velocity to about 3,9 km/s, after which the spacecraft captures into a 2 RS 100 day elliptical **orbit using high thrust bimodal propulsion system with NH3 propellant. The total electric AV** prior to capture is 1.5 km/s (0.5 year bum time) for the 2EJGA mission, and 4.5 km/s (1.5 year burn time) for the 2EGA mission.

After capturing the SRB spacecraft it releases a micro-orbiter, leaving it in the initial moderately inclined, highly elliptical orbit from which it can survey the whole Saturn system. The SRB spacecraft then performs an electric propulsion apoapsis bum to raise itself into an equatorial orbit with its periapsis at 3 RS (AV = 216 m/s), which is safely outside the ring system of Saturn (except for the ethereal E ring). It then releases a micro-orbiter in this orbit. This second microspacecraft will be in an orbit that allows it to periodically fly by Mimas, Enceladus, Tethys, Telesto, Calypso, Dione, Helene, Rhea, Titan, and H yperion and get fairly close to Iapetus (14.7 degree inclination). The SRB spacecraft then perform another NEP AV of 659 m/s to raise it's periapsis from 3 RS to 20 RS which is the distance of Titan from Saturn. A series of gravity assists are then performed to lower the apoapsis from 132 RS to close to 43 RS, which puts the spacecraft into a 32 day orbit around Saturn which is synchronous with Titan (which has a 16-day orbit). At Titan encounter two micro-orbiters are released into elliptical orbits which later are turned into low polar orbits with perpendicular orbit planes, Also released are 8 entry probes each carrying a small robotic aircraft.

Each aircraft has a mass of 10 kg and a wing area of 0.5 m2. Titan has a surface atmospheric density of about 5 kg/m3 and a gravity 1/7th that of Earth, conditions that are very favorable for heavier-than-air aviation. Under these conditions the aircraft will only have to move at an airspeed of 4.8 m/s to stay aloft, and with an L/D of 20, will require a thrust of 0.7 N and thus an effective propeller power of 3.4 W. This can easily be provided by the aircraft's 20 Wt RHU, since in Titan's 90 K atmosphere, dynamic conversion of heat to electricit y at efficiencies greater than 60% should be feasible. The aircraft thus has 12 We, which allows it to fly continuously as well as operate strobe flashlights to support imaging in the visible light range, as well as continual radar sounding of the ground to reveal subsurface features and assure safe flight. If the plane is designed as a tilt-rotor with pontoons, it can be made capable of soft landing on the ground/ocean, allowing direct sampling of the surface. Ascent from such a condition requires burst power of 70 We, which can be r-made available by expenditure of a small charge stored in the aircraft's battery. The aircraft will come into contact with the low orbiting microspacecraft about once every other day, at which time they can uplink all their data. The microspacecraft are equipped with 10 Gb memories, allowing each one to store up to 50,000, 512 X 512 black and white images, or comparable data. Every 32 days the SRB spacecraft will fly by, and the orbiters will dump all the collected data for relay to Earth. The science payload mass required for this mission is shown in Table 4.

Table 4. Science Payload of SRB Spacecraft for Saturn Exploration Mission

| | |
|---|---|
| SRB S/C Instruments | 20 kg |
| Saturn High Inclination Orbiter | 13 |
| Saturn Highly Elliptical Equatorial orbiter | 13 |
| (2) Titan Micro-Corn Orbiters | 50 |
| (8) Titan Aircraft | 160 |
| Total Science Payload | 256 kg |

The SRB spacecraft launched by an Atlas 2AS can deliver a 256 kg science payload.

## NEPTUNE. PLUTO AND MAIN BELT ASTEROIDS MISSIONS

The Neptune and Pluto missions are still being studied to determine how to use SRB to get instruments or microspacccraft in orbit within 5 years from launch. The Main belt asteroids missions are also being studied using the SRB spacecraft to deliver microspacecraft to several asteroids,

## CONCLUSIONS

1. A 10 kWe space reactor bimodal,(SRB), spacecraft could transport 10 or more microspacecraft to Jupiter and Saturn. The SRB would then locate each microspacecraft at scientific targets of interest around Jupiter and Saturn. The microspacecraft would collect scientific data and transmit that data to the SRB spacecraft which would process the data and transmit the processed data to Earth.

2. Sustained high power, 10 kWe, in orbit around Jupiter and Saturn would provide excellent scientific data return from several microspacecraft operating as a network or separately at strategic locations around Jupiter and Saturn.

3, An SRB could provide communication and data transmissions for decades to support many new low cost microspacecraft launched to Jupiter and Saturn orbits for specific scientific information in future years.

4. The SRB could also enable obtaining new scientific data from Jupiter and Saturn and their moons and rings with ita own instruments, high power and very high communication data rates.

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